Nonlinear Time-Dependent Currents in the Surf Zone

Donald N. Slinn
Department of Civil and Coastal Engineering
University of Florida
Gainesville, FL 32611-6590
Phone: (352) 392-9537 x 1431 Fax: (352) 392-3466 E-mail: slinn@coastal.ufl.edu

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LONG-TERM GOALS

The goals of this work are to develop better understanding and predictive capability for nearshore currents forced by breaking waves in the surf zone.

OBJECTIVES

The major tasks have been to:
(1) Couple the wave field to the evolving currents in physical-mathematical models for situations that produce alongshore and rip currents. As currents evolve, the distribution of surface wave breaking adjusts because of the wave refraction caused by the currents. Subsequently, the momentum input to the currents is altered. We have examined the influence of feedback from the currents on the wave radiation stress gradients that parameterize momentum forcing from wave breaking.
(2) Examine rip current dynamics for different parameter ranges of wave height, incident wave angle, bottom friction, and beach bathymetry.
(3) Demonstrate the influence of undertow and cross-shore mass flux in on the location of the peak alongshore current.
(4) Utilize the model in a forecast mode in collaboration with field experiments led by R.T. Guza on Scripps beach.

APPROACH

The work involves theoretical development, numerical computations, and comparison with field data. We use both a three-dimensional, depth dependent model and a depth-integrated and time-averaged (with respect to the wave period) shallow water equation model including parameterization for the wave forcing effect, horizontal diffusion, and bottom friction (Slinn *et al.*, 1998, 2000).

WORK COMPLETED

The depth-averaged model has been modified to couple the wave refraction with the evolution of currents. The effects of wave-current interaction have been tested on rip currents (Yu and Slinn, 2003) and alongshore currents (McIlwain and Slinn, 2003). A new three-dimensional model has also been implemented to demonstrate the importance of the undertow on the cross-shore distribution of the alongshore currents (Splinter and Slinn, 2003). Modeling of drifters released at Scripps Beach with

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R.T. Guza and W.R. Schmidt has been used to understand the physics of a complex double rip-channel system.

RESULTS

Our new 3-D Large-Eddy Simulation (LES) nearshore circulation model implements the Smagorinsky sub-grid scale closure scheme. It models the wave-phase-averaged, time-dependent, low-frequency currents, in a curvilinear, bottom conforming, σ-coordinate system, with a rigid, free-slip lid at the surface (Winters et al, 2000). Bottom stress is included with a no-slip condition at the bottom boundary and resolved through the use of a vertically clustered grid. The model is periodic in the alongshore direction, with a shore parallel sand bar located approximately 80 meters from the shoreline. The grid resolves centimeter scales near the seabed, adequate for the LES turbulence closure scheme to produce realistic time-averaged vertical velocity profiles. Figure 1 illustrates the problem geometry and grid coordinate system used in the model. The physical domain is 200 m x 198 m in the *x-y* direction, reaching a depth of 4.5 m at the offshore boundary following a depth profile approximate to topography measured at Duck, North Carolina, October 11, 1990, as part of the DELILAH field experiment (Lippmann et al., 1999). The beach topography has alongshore-uniform bathymetry and includes a distinct shore-parallel alongshore bar–trough system. The computational domain is composed of 129 x 129 x 33 (549,153 total) grid points. The grid is clustered in both the vertical and horizontal directions with additional grid resources deployed near the shoreward boundary and the seabed. The grid spacing is on the order of 1 meter horizontally, and 10 centimeters vertically, decreasing in the vertical near the seabed. The wave field is coupled to the mean currents through the radiation stress gradients, where the wave breaking is calculated using the Thornton-Guza sub-model.

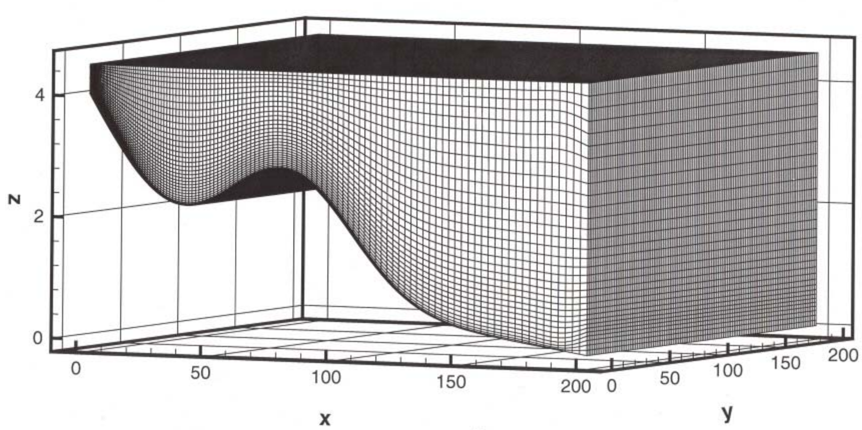

Figure 1: Physical grid layout used in numerical simulations to represent the beach profile at Duck, North Carolina, October 11, 1990, as part of the DELILAH field experiment.

We present contours of the alongshore surface currents *v(x,y,t)* for two Cases during times of flow development in Figure 2. The first major difference between depth uniform (C1) and depth dependent (C2) forcing is that instabilities of the alongshore current develop much sooner with the depth dependent flow. The second major difference is that the strength that the surface current (and depth averaged current) achieves is much stronger before breaking down into instability and turbulence in the case of depth uniform forcing. The third significant difference between the flow development is that the alongshore wavelength of the initial instabilities are much longer (of order 100's of meters) for the depth uniform current, but on the order of 10's of meters for the depth dependent current. The fourth interesting flow feature is that the peak alongshore remains centered over the sand bar for the depth uniform forced current after the flow becomes unstable, but it moves inside the sand bar, into the trough for the depth dependent forcing.

Clearly there are very significant implications for the behavior of the alongshore current depending on the depth dependence of the forcing and three-dimensionality of the flow. We note that the behavior in the simulation with depth uniform forcing case is qualitatively similar to the flow development that we have observed in previous numerical experiments with depth-averaged models (Slinn et al, 1998, 2000). The distinctive features observed here for the depth dependent forcing: rapid instability of the alongshore current, small-scale instabilities, and the shoreward shift of the peak current are entirely new. The most interesting aspect of these new observations are that they may have a very logical, and previously neglected explanation (discussed below), and that the shoreward shift of the peak alongshore current is similar to puzzling phenomenon that has been observed in nature (Church & Thornton, 1993). We contend that the depth dependent forcing more closely resembles the situation in most natural beach situations, and that the newly modeled behavior in the 3-D model is a more consistent approximation of nearshore current behavior. Insight into the dynamics that produce the different cross-shore distributions of the alongshore currents is gained by examining vertical cross sections of the velocity (Figure 3).

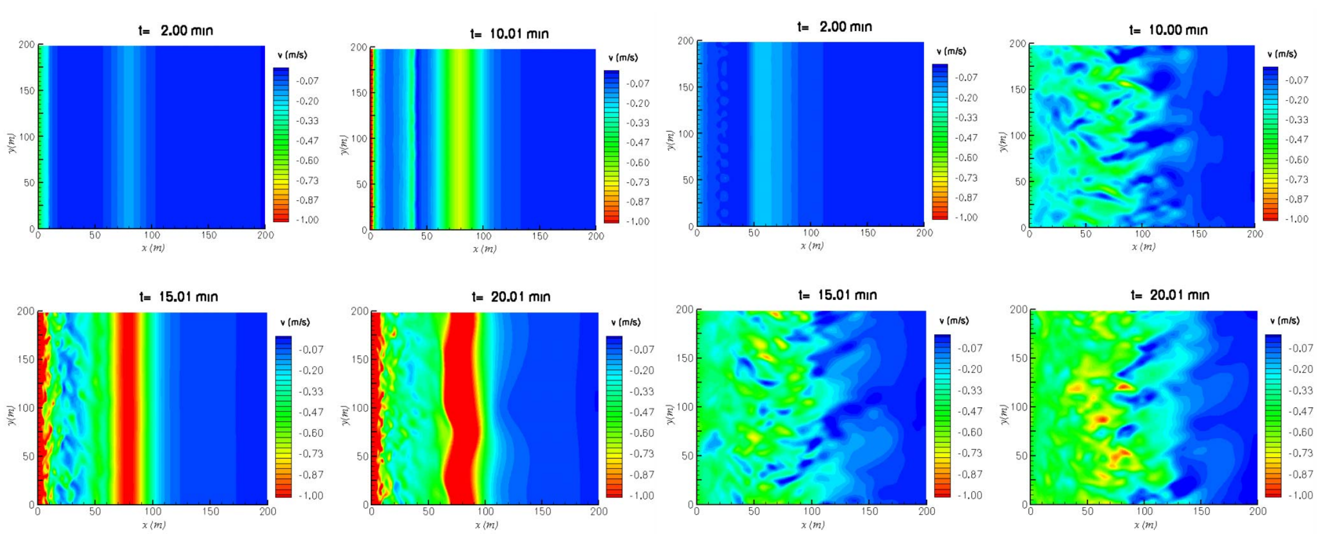

Figure 2: x-y plots of the surface alongshore velocity field for Cases 1 (two left columns) and 2 (two right columns) during phases of flow development. The offshore wave direction is 30^o. For the depth uniform forcing the current remains more organized and centered over the bar, located at x = 80 m, producing currents over 1 m/s and by t = 20min, long wavelength instabilities are developing. For depth dependent forcing, the flow destabilizes into smaller scale motions more rapidly, diffuses horizontally, and the peak currents of approximately 0.5 m/s drifts shoreward of the bar crest.

The cross-shore and depth distribution of the alongshore velocity profiles reveal effects of 3-D mixing and preferential cross-shore advection. It appears that the physical explanation has two major components. The first is that much stronger cross-shore circulation develops for the depth dependent forcing. When $F^{(x)}$ is depth uniform, little cross-shore circulation is produced, rather, a barotropic cross-shore pressure gradient balances the forcing. When $F^{(x)}$ is depth dependent, a strong undertow develops rapidly, compensated by a shoreward mass flux in the top half of the water column. The reason this is dynamically important to the depth averaged alongshore current is that $F^{(y)}$ and $v(x,y,z)$ are also depth dependent and there is a much stronger alongshore current in the top half of the water column than in the bottom. Thus the faster near surface alongshore current is advected shoreward (into the trough) while the weaker bottom alongshore current drifts offshore. The net effect is a shoreward shift of the alongshore current maxima. Interestingly, in the examples we have investigated, the depth-averaged maxima becomes balanced in the trough.

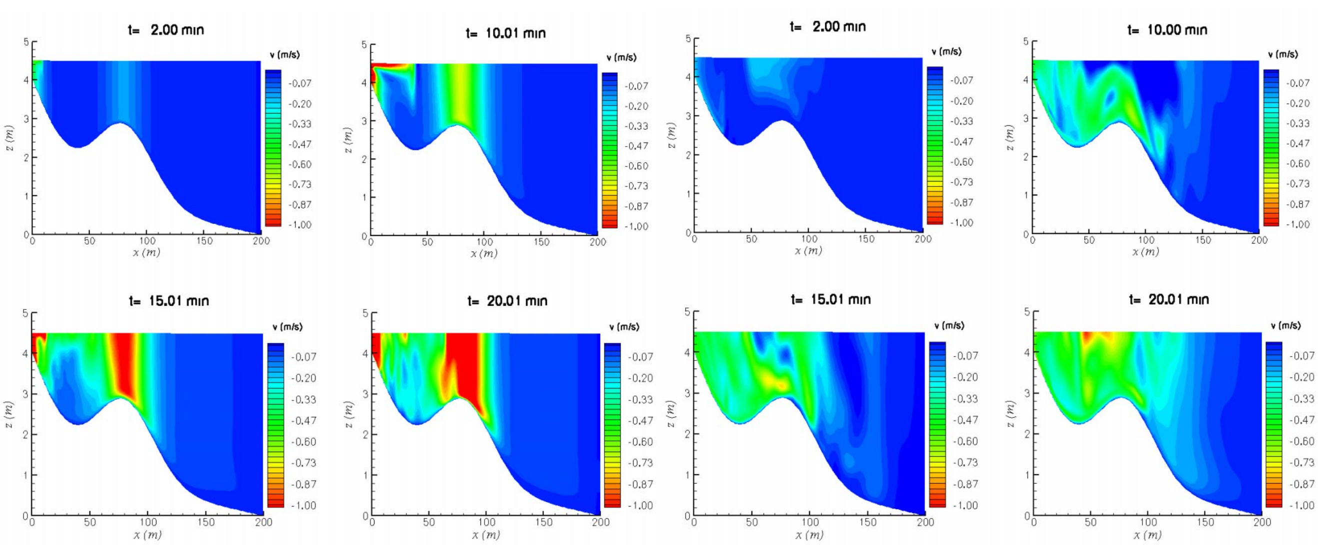

Figure 3: x-z contour plot of alongshore velocity at y = 99 m for Cases 1 and 2. In Case 2 (right panels) the alongshore current generated at the shoreline is pulled seaward from the undertow which can be seen at t = 10 min. The depth dependent forcing case produces alongshore currents that encompass more cross-shore area between the bar and the shoreline due to mixing between the 2 areas of concentrated forcing.

The net effect of this cross-shore dispersion on the mean alongshore current is similar to including a roller model to the shoaling surface wave sub-model in order to shift the location of wave momentum input shoreward. We have not included a roller model in the formulations of the T-G model that we have implemented here. Alternate hypotheses have been set forward previously to explain current maxima in the trough. A leading candidate is the effect of topographically coupled alongshore pressure gradients (Slinn, et al., 2000). We have no mean alongshore pressure gradients in this model because the bathymetry is alongshore uniform, and we use steady forcing without wave-current interaction (Yu & Slinn, 2003).

Complementary lines of investigation have considered net effects of the undertow on depth-averaged currents, such as the formulations in the quasi-3D implementation of Shorecirc (*e.g.,* Putrevu and Svendsen, 1999). They have not observed current behavior qualitatively similar to what we see here. It appears that the reason is that in their formulation, they use the quasi-3D information primarily to estimate an isotropic horizontal diffusion coefficient. This would be an excellent approximation if the alongshore current were depth uniform because the shoreward mass flux in the top half of the water column would carry equal amounts of alongshore momentum as the undertow carries offshore. Perhaps this would be the best approximation for plunging breakers that vigorously stirred the water column at high frequency, or if the bottom boundary layer of the alongshore current was very thin. If, however, the alongshore current is depth dependent, either because the momentum input is depth dependent, or because bottom friction develops a thick boundary layer, then it is reasonable that the net effect of three-dimensional cross-shore circulation would be to produce, non-isotropic, preferentially shoreward diffusion of the alongshore currents.

The cross-shore distribution of the depth- and alongshore-averaged alongshore velocity profiles are shown in Figure 4 during times of flow development. In Case 1, after the flow becomes turbulent, around t = 25 min, the alongshore current spreads into the trough, but a local maxima persists over the sand bar, near x = 80 m, with a velocity near 75 cm/s. In Case 2 (right panel) the peak current has shifted to near x = 60 m and the shoreline jet is much weaker. An approximate steady state has been achieved for t ≥ 40 min, though the offshore turbulent diffusion is continuing to strengthen the current for x > 150 m.

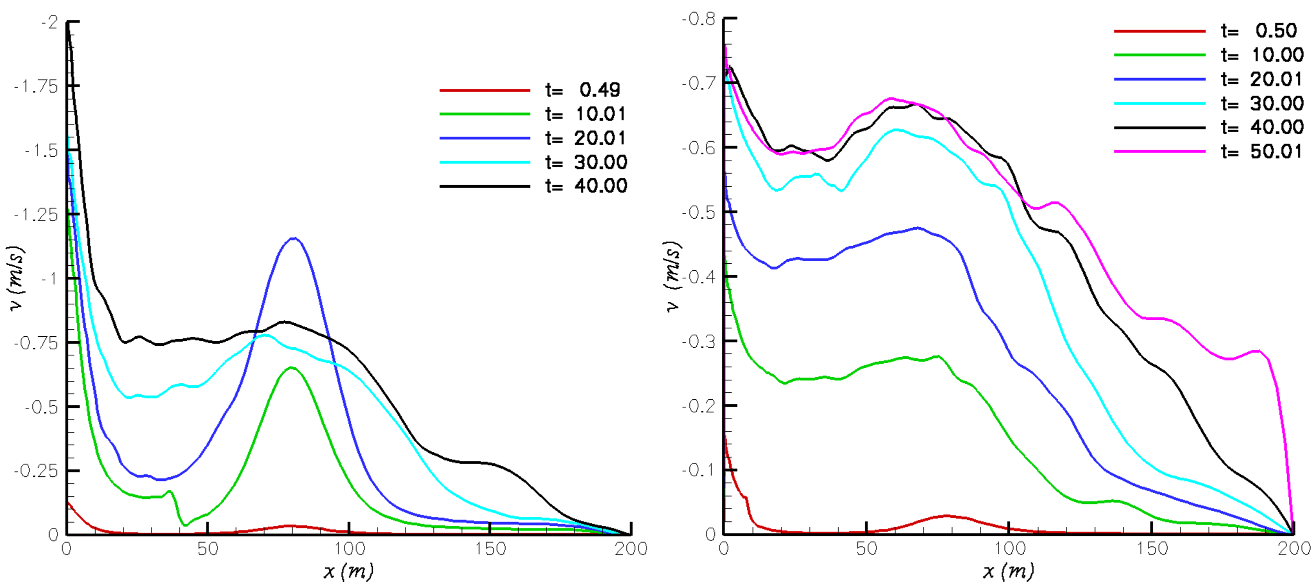

Figure 4: Alongshore and depth-averaged alongshore velocity profiles for Cases 3 and 4.

IMPACT/APPLICATIONS

Improved understanding of the near shore environment has potential benefits for society in several areas. These include shore protection against beach erosion, understanding the behavior of shoaling waves, keeping waterways open for shipping in harbors, ports and inlets, safety for recreational beach users (e.g., from dangerous rip currents) and in defense of the nation when activities encompass littoral regions. We will have a strong indication that we understand and can quantify important nearshore processes when predictive models can match field observations.

TRANSITIONS

Our major transitions have been to begin real-time forecasts of nearshore circulation and simulated Lagrangian drifters for Scripps Beach in collaboration with R.T. Guza and W. Schmidt of S.I.O. and to examine alongshore currents with our new 3D model.

RELATED PROJECTS

1. R.T. Guza at Scripps Institution of Oceanography has collected valuable field data using drifters and in-situ instrumentation for calibration and testing of our model skill.

2. A group of near shore researchers, led by Jim Kirby at the University of Delaware, are developing near shore community models. We expect to benefit from and contribute our ideas to their modeling studies.

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PUBLICATIONS

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